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prepared for

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HEAT TRANSFER LABORATORY

MECHANICAL ENGINEERING DEPARTMENT

UNIVERSITY OF MINNESOTA

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(October 1 1964 to December 31, 1964)

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INTRODUCTION

The Heat Transfer Laboratory at the University of Minnesota is engaged in a program of theoretical and experimental investigation of the heat transfer phenomena occurring in electrical arcs under NASA Contract No. NAS3-2595. The project manager for the contract is Mr. J. Sovey of the Electrothermal Technology Section, Lewis Research Center. This report covers work performed during the sixth reporting period (October 1, 1964 to December 31, 1964). The sixth reporting period was devoted to performing experiments with argon in the arc tunnel using both a single, plane, segmented anode and a double, non-segmented anode arrangement. An optical system for focusing the arc in the tunnel on the entrance slit of the spectrograph was designed. Finally, an explosion proof exhaust line was installed for expelling hydrogen from the arc tunnel.

SUMMARY OF PROGRESS

Experiments with Segmented Anode

During this reporting period the segmented anode was studied in several phases. Arc voltage oscillograms and high speed movies were taken for comparison purposes of the arc operating with both the segmented and non-segmented anodes because initially it was thought that the sharp edges of the segments might be preferred arc attachment points. In fact, the edges were purposely rounded slightly in hopes of lessening the possibility of this difficulty. Figure 1 shows two typical oscillograms of the voltage fluctuations which occur with the fluctuating arc mode. The same characteristic sawtooth-shaped waveform is observed with both anodes which indicates that except possibly for some small fluctuations the segment edges do not disturb the arc. The small fluctuations in the voltage trace which appear more frequently in the oscillogram shown for the segmented anode may or may not be traceable to edge effects.

Fortunately, no preferred attachment points were observed in the high speed movies. Furthermore, the arc attachment point moved steadily along the surface of the segmented anode (fluctuating mode) apparently unaffected by the 0.010 inch layer of synthetic mica separating each segment. The current through the anode column seems to split as the attachment point moves from one segment to another--that is, part of the current flows through one segment and the rest flows through the other although the column itself does not visibly split into two portions. This splitting effect allows a gradual transition of the current flow from one segment to an adjacent segment. This effect is also observed in the oscillograms in Figure 2 which show the time dependence of the current flow through each segment, the total current, and the arc voltage. The traces of the segment currents are double exposures--one exposure shows as a straight line and indicates the zero current reference; the other is the actual current trace for the particular segment. Note how the current trace appears to gradually decay in one segment while it builds up in the next, an observation that may be explained by the splitting effect.

Each sudden drop in the voltage (Fig. 2) is accompanied by a current flow in one of the upstream segments indicating that the arc has restruck. After restrike, the arc terminous travels downstream in sequence from segment to segment until another restrike occurs. It is interesting to note that the total current is essentially constant with respect to time. Unfortunately all the traces still have a small amount of stray pickup superimposed on them even though extensive shielding has been employed. The main source of this disturbance is from the changing magnetic field around the current lead coming from each segment. The transition of the 100 ampere current from one segment to the next occurs in the order of 0.1 millisecond or less giving rise to dI/dt values of 10^6 amp/sec. Presently all but a small portion of the current carrying leads are shielded, and the oscilloscope leads are double shielded. Future plans call for further shielding and more strategic placement of component parts.

The segmented anode was also used to measure the average field strength in the arc and provide some indication of the fall voltages. By disconnecting all the power leads to the segments except one far downstream, the arc attachment was forced to a point distant from the cathode. Then the assumed potential of each segment was measured with respect to the cathode with a high impedance vacuum tube voltmeter.

A typical result is shown in Figure 3. Several sets of data were taken for various gap distances S. As S was increased, the value of $U_a + U_y$ also increased while U_c and the slope of the potential distribution curve remained about the same. These measurements should provide a fairly accurate indication of the average field strength along the arc column. The values of U_c and $U_y + U_a$ established by this method still need further interpretation.

An attempt was made to statically measure the voltage required for restriking the arc. The current leads for all but one of the segments were disconnected as described before forcing the arc attachment downstream. Then a separate power supply was connected between the cathode and one of the upstream segments. The idea was to increase the voltage of this auxiliary power supply until restrike occurred in the form of a self-sustained discharge. By increasing the voltage slowly, it was hoped that a complete voltage-current characteristic of the breakdown could be measured.

The measurements, however, have not been successful. As the voltage was increased slowly, first a non self-sustained discharge developed which the gas flow prompted distorted into a hairpin shape which could be detected as soon as a self-sustained arc was established. The measured values are no longer meaningful because in the real case the breakdown occurs too fast for the hairpin shaped column to form, and a completely different characteristic is associated with the phenomena. Apparently this technique will only work for zero flow conditions.

Another approach which might be tried in the future would be to measure the breakdown characteristics of the restrike phenomena with a dynamic method. The voltage of the auxiliary power supply would have to be increased to breakdown potential at a rate which is one or two orders of magnitude faster than the blowing velocity. The resulting characteristic would then be measured with an oscilloscope.

Experiments with Double Anode

The double anode configuration consists of two plane anodes which are situated opposite each other in the top and bottom of the test section, respectively. As shown in Figure 4, the flow is parallel to the anode surfaces. The details of the anode design were described in Quarterly Progress Report No. 5 (under the old name, "Two-Dimensional Electrode Geometry") and will not be repeated here.

The construction of a double anode was completed during this reporting period, and some experiments in argon were run to determine the symptomatic behavior of the arc under various operating conditions. In order to study the arc's behavior in detail, high speed movies were taken simultaneously of the arc and an oscilloscope monitoring both the arc current and voltage. (Two typical movies of the fluctuating mode were delivered to NASA by Mr. Hunczak, technical manager from Lewis Research Center, after his visit to our laboratory during this reporting period.)

The two anodes are electrically insulated from the test section so that the current through each anode can be measured independently. A separate current shunt is attached at one end to each anode and at the other end to a common lead from the positive terminal of the power supply which is grounded. Thus, the two anodes are kept at the same potential. The distance between the two anodes is 17.6 mm.

The high speed movies show that for the operating conditions chosen ($50 < I < 100A$, $100 < P < 760$ mmHg, $O < V < 100$ m/sec), two arc modes exist as found before--a steady mode and a fluctuating mode. The steady mode is characterized by a smooth voltage trace on the oscilloscope and a stationary, contracted attachment of the arc to one of the anodes. So far the steady mode has not been observed with a simultaneous attachment to both anodes using argon. It is felt, however, that this condition might possibly be achieved by either lowering the pressure, increasing the input power, or decreasing the anode spacing.

The fluctuating mode is characterized by a sawtooth-shaped voltage trace on the oscilloscope and a simultaneous traveling downstream of the contracted arc attachment point on the anode with repeated restriking of the arc upstream between the arc cathode column and one of the anodes. In general, the restrike phenomena seems to be nearly random as neither anode nor position on them is usually a preferred restrike point when the cathode is properly centered between the anodes. The arc may restrike on the same anode or jump across to the other anode. A typical excerpt from one of the high speed movies is shown in Figure 7. The voltage and current traces are synchronized with the recorded arc event. At the higher flow velocities and pressures, a wiggling pattern is observed in the cathode column which seems to influence the restrike phenomenon. The "humps" in the wiggles bring the arc column closer to one or the other of the anodes causing a more favorable restrike condition. The presence of these wiggles may increase the frequency of restriking by a factor of 2 to 10.

In our previous reports it was mentioned that the anode jet deflects the cathode column away from the anode to which the arc is attached, the amount of deflection being greater for higher currents. By having a second anode positioned opposite to the first, the deflection causes the tail of the luminous column to actually touch the second anode. It was initially thought that the arc might jump to the second anode at this point. This phenomenon has not been observed in the high speed movies, however, for the range of parameters tested, although a narrower anode spacing or another test gas may cause its occurrence.

Usually the cathode was adjusted vertically for the fluctuating arc until the average current flow through each anode was about the same. For this condition the cathode column appeared to be deflected downward slightly with respect to the anode surfaces indicating that the flow was perhaps not quite uniform in the test section. A quick check with a pitot probe under cold-flow conditions showed that the flow velocity was about 5 per cent greater near the top of the test section. This nonuniformity appears to be due to the assymmetry of the smooth inlet to the test section caused by the addition of the second anode (Fig. 4). The nonuniformity in the flow plus the need for varying the anode spacing has led us to the conclusion that it would be profitable to design and build a new double anode assembly which is both symmetric and adjustable.

Optical System for Spectrometric Measurements

An optical system has been designed which will permit spectrometric measurements of any plasma in the arc tunnel with the 2.0 meter spectrometer which is located in an adjacent room.

The initial considerations of various systems included using several different optical path lengths, using fiber optics, relocation of, and even scanning the arc with the spectrograph, and use of concave mirrors. Selection of the best optical path was guided by our concern to interfere as little as possible with other experiments in the arc tunnel.

The use of a fiber optic image conduit was investigated. It turns out that a conduit running from the test section to the spectrograph slit would have extremely large intensity losses due to absorption, as well as being out of our price range. Alternately, a one meter length of image conduit could have been used to locate on any position in the arc; however, a smaller, more economical unit would not have the resolution needed. In this case, the optics from the image conduit to the spectrometer would still have had to be similar to the optical system finally selected.

Any major fixed relocation of the spectrometer would have meant loss of flexibility for measurements in the original test area. The mounting of the spectrometer on a movable and adjustable stand was considered but would have involved fairly complicated design and construction problems in addition to the always necessary optical system.

A system composed of two large concave mirrors was also investigated. In this design the first mirror could be rotated in two dimensions to scan the arc. The second mirror must be large enough to catch the spreading light beam. Though the system had merit, the main disadvantages were the additional path length and resulting increased size of components, due to the use of mirrors instead of lenses; the odd angles necessary at the mirrors in the system, which must have certain values to obtain the proper orientation of the arc image on the spectrograph slit; the "awkward" location of components; and the fact that spherical mirrors, though achromatic, cannot be corrected for spherical aberration.

<u>The basic design problems</u> that bear mentioning involve distortion, resolution, intensity losses, construction, and economy. In addition, we are concerned with uniformity in the percentage of light intensity losses over the image, calibration of intensity variation with wavelength, and flexibility in future experiments.

Brief experiments were made with a simple prototype to study the approximate effect of the number of components on distortion and to some extent resolution. We found that six lenses and four mirrors (16 surfaces) of average quality produced an image that was poor; whereas, three lenses and three mirrors (9 surfaces) produced a good, reasonably sharp image. The cost of high quality optical components dictated that a somewhat "simpler," direct, and less convenient system with 10 or less surfaces of average quality be used. The above experiments were made with scaled down components and path lengths. It is hoped that the larger components of average quality will not decrease image quality.

Light intensity losses depend mainly on the reflection and absorption losses and the relative size of the optics. Proper coatings can decrease reflection losses of lenses and increase reflection from mirrors. Assuming uncoated components, the overall intensity losses in the proposed system are tolerable.

A non-uniform intensity over the image can occur from a uniform source if a component is smaller than the beam of parallel rays striking it. Beams from object points further off the axis have less area incident upon the optical component than beams from points nearer the axis. The components in an optical system used for measuring intensities should, therefore, be adequately large. Such is not the case in the usual design of the grating size of the spectrometer where one optimizes among resolution, overall intensity losses, and uniformity "in percentage" of intensity losses over the image. In our design proper placement of the diaphragm, or aperture stop, favors the last at some sacrifice of resolution and overall intensity.

Intensity losses also vary with wavelength. This effect is larger with uncoated mirrors. To correct for wavelength, the optical system will be calibrated with a carbon arc. If the optical system as designed with large components of average quality gives a good image, we may obtain coated mirrors to decrease overall and chromatic variations in intensity.

Our aim is to keep the construction and components as simple and economical as allowable, and yet not sacrifice flexibility, so necessary in a research laboratory.

The optical system, called the plasmascope, which emerged from the initial considerations and design problems discussed above, is simple, direct, and flexible. It has a basic magnification of unity because the plasmas to be viewed in the near future are slightly smaller than the spectrograph slit. The magnification can be varied by adding or changing lenses.

The plasmascope contains two large, coated, achromatic lenses, a large iris diaphragm, and five front surface aluminum mirrors. An additional mirror is used in calibration. The arc (object) lies in the focal plane of the first lens. Rays from any object point, leaving the first lens, are parallel to each other. The second lens focuses the image in its focal plane on the spectrograph slit. Three mirrors are used to focus on a desired part of the arc. The remaining two mirrors route the light beam to the spectrograph. Figures 5 and 6 show the floor plan and optical diagram of the plasmascope and spectrometer respectively. Figure 6 also indicates the paths of beams from object points on and off the axis, and the resulting uniform intensity distribution over the grating (with a uniform source).

The first lens or objective (D = 6 in., f = 90 in.) and three mirrors (6 x 8 1/2 in.) are mounted on a converted U.S. No. 1 hand mill. The unit acts as a plasma scanner to locate the image of the plasma on the spectrograph slit. Movement of the mill bed is motorized to allow positioning from the spectrometer.

The calibration arc is also mounted on the plasma scanner such that only an additional mirror need be swung into place before calibrating. The mirror has a corrective coating which results in a negligible correction for wavelength in relative intensity measurements.

The two mirrors, the iris diaphragm, and the other lens are mounted on an optical bench next to the wall parallel to the spectrometer. The long optical bench will also serve in the alignment of the optical system, as a mount for future optical components under different magnifications and in auxiliary optical experiments.

The iron arc stand, used for wavelength determination and some qualitative analysis, lies on the optical bench beside the spectrometer; therefore, it is available when needed without disturbing the optical system from the arc tunnel or original test facility. The bench is also located to serve as an optional optical path from the arc tunnel to the spectrometer.

A discussion of the methods used for taking the spectrometric measurements is given in references (1) and (2).

Preliminary Experiments with Hydrogen

No experiments with hydrogen in the arc tunnel were performed during this reporting period as originally planned because of an unexpected delay in the installation of the hydrogen exhaust line. Despite the temporary delay due to the late arrival of materials, the hydrogen exhaust line required by our Safety Division is now completely installed, and the hydrogen experiments will be started soon.

PROPOSED WORK

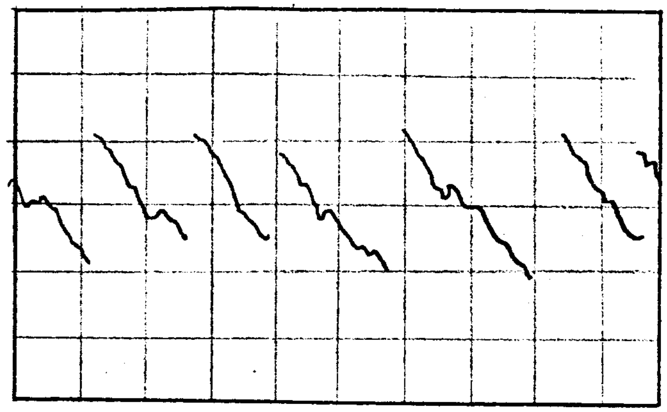
The seventh quarter of the contracting period will be devoted primarily to the following tasks:

1) Measurement of the "local" heat transfer to the anode by means of the segmented anode.
2) Experiments with hydrogen.
3) Construction of the plasmascope to be used for the spectroscopic measurements.
4) Design and construction of a symmetrical double anode with adjustable spacing.
5) Design and construction of a cylindrical anode to be inserted in the existing test section.

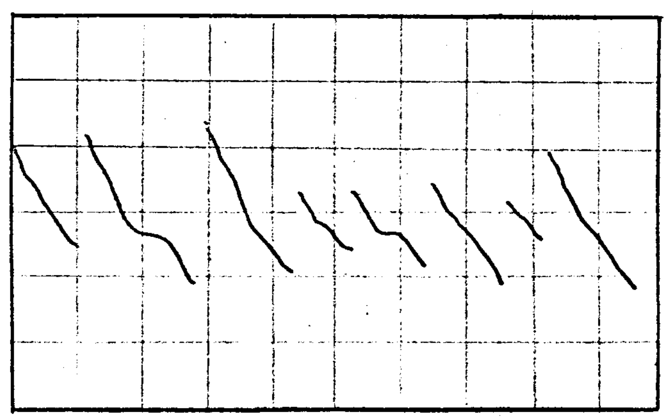
References

(1) Cremers, C. J., "The Spectrometric Measurement of the Temperature Field in an Arc with a Transpiration Cooled Anode," Ph.D. Thesis, University of Minnesota, December, 1964.

(2) Cremers, C. J., Pfender, E., "Thermal Characteristics of a High and Low Mass Flux Argon Plasma Jet," HTL TR No. 57, July, 1964. (To be published as an ARL Technical Report.)



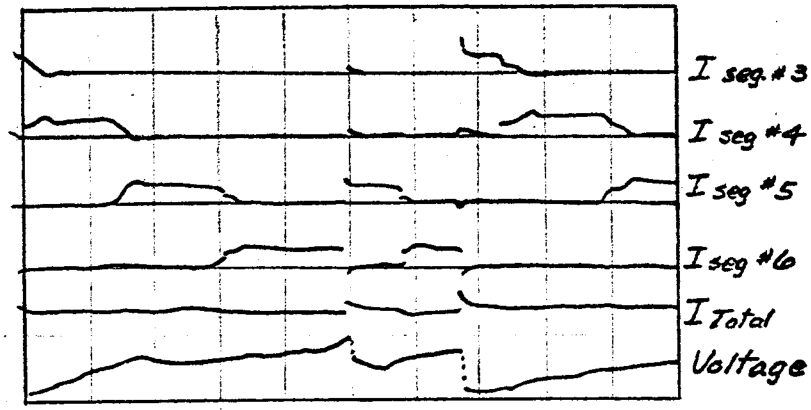
(a) Segmented Anode



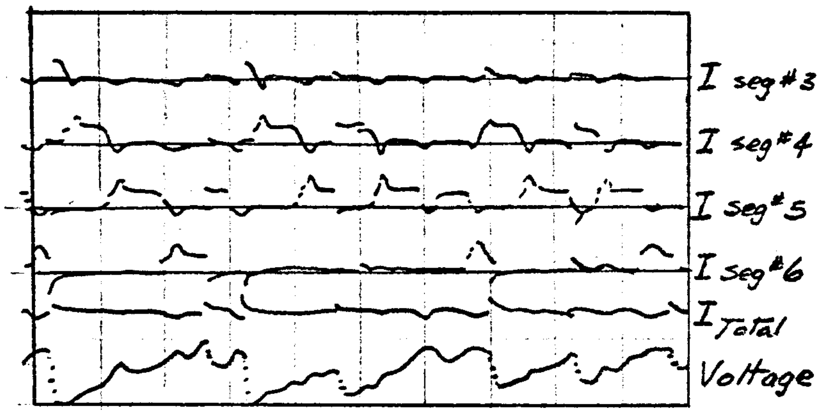
(b) Solid Anode

$P = 760$ mm Hg, $I = 100$ Amps, $v = 60$ m/sec
$s = 7$ mm, 0.1 V/cm, 0.1 ms/cm

Fig. 1 OSCILLOGRAMS OF VOLTAGE FLUCTUATION



P $P = 760$ mmHg $I = 100$ Amps
V $v = 20$ m/sec $s = 8$ mm
400 A/cm, 20 V/cm, 0.5 ms/cm



$P = 760$ mmHg $I = 100$ Amp
$v = 50$ m/sec $s = 7$ mm
400 A/cm, 20 V/cm, 0.5 ms/cm

Fig. 2 OSCILLOGRAMS of CURRENT & VOLTAGE

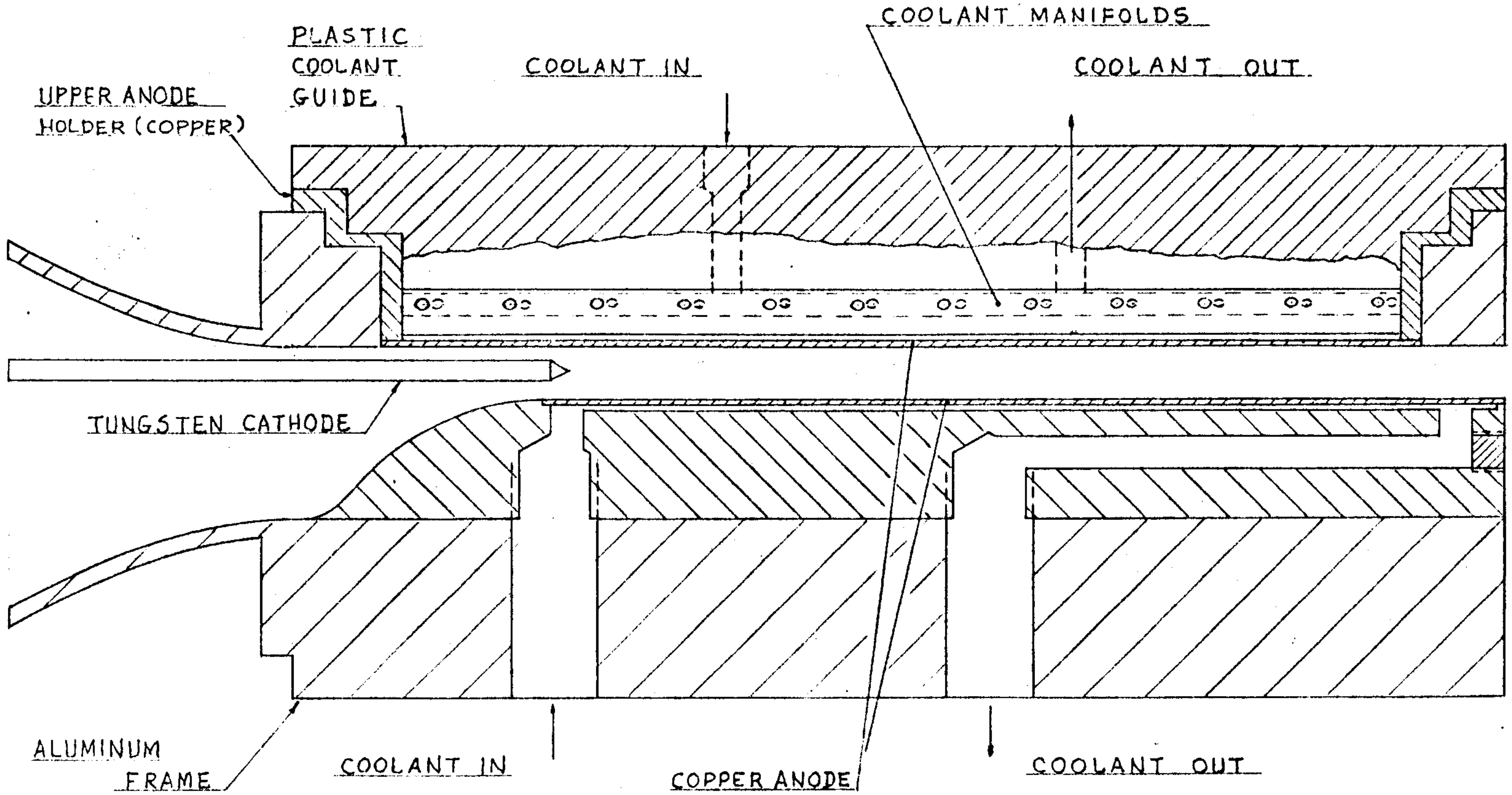


FIGURE 4: SCHEMATIC OF TWO-DIMENSIONAL ANODE GEOMETRY

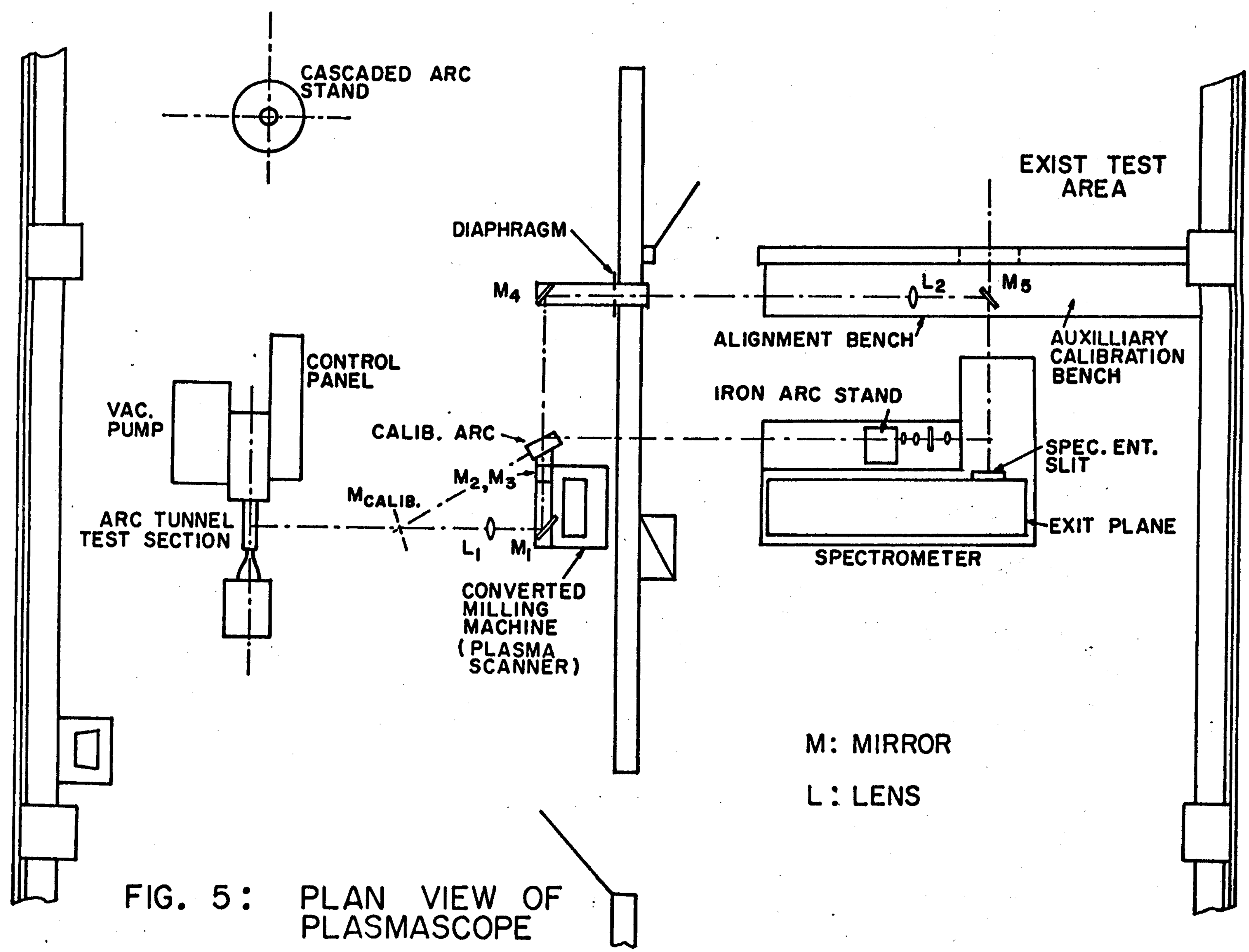


FIG. 5: PLAN VIEW OF PLASMASCOPE

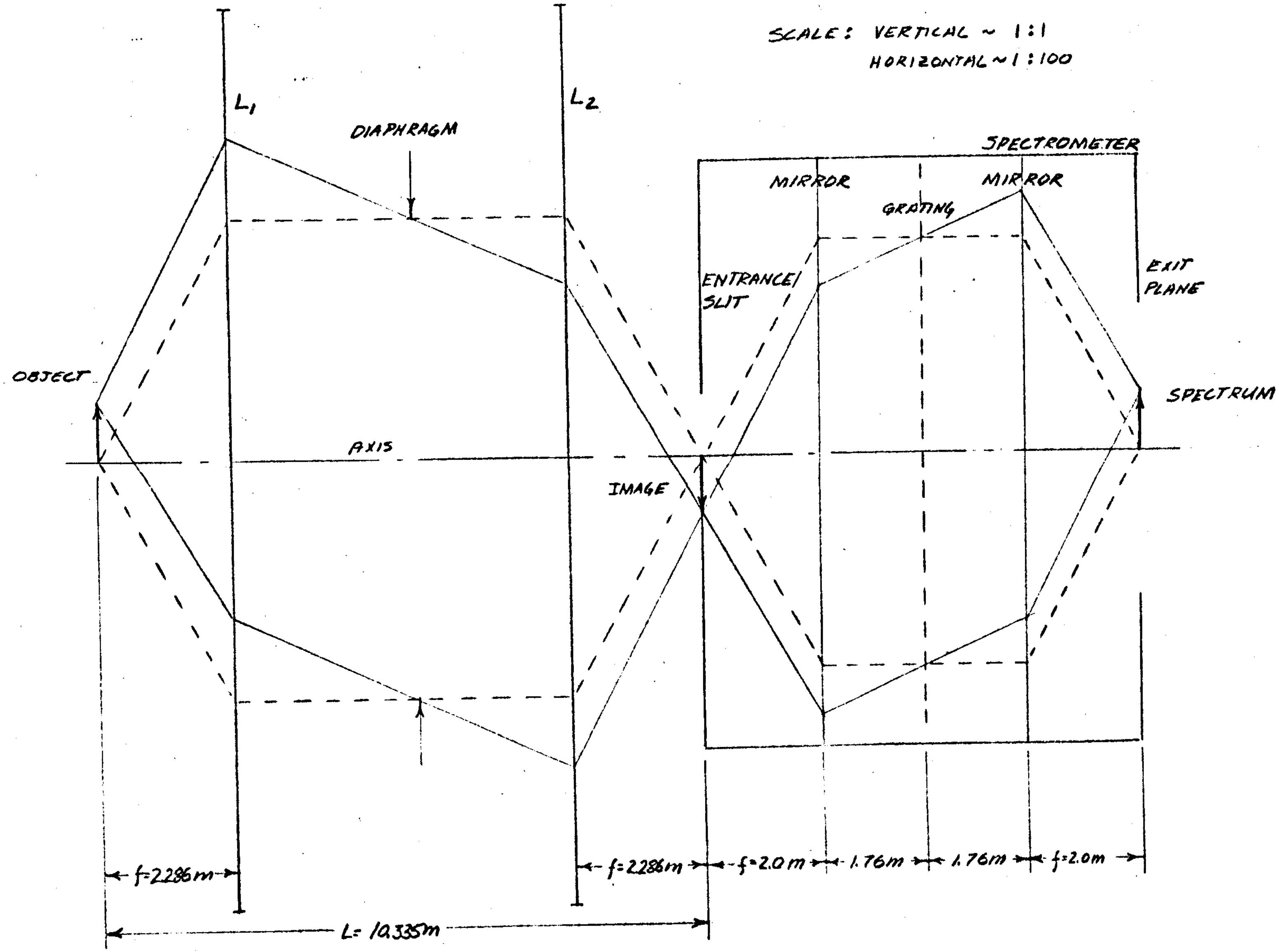
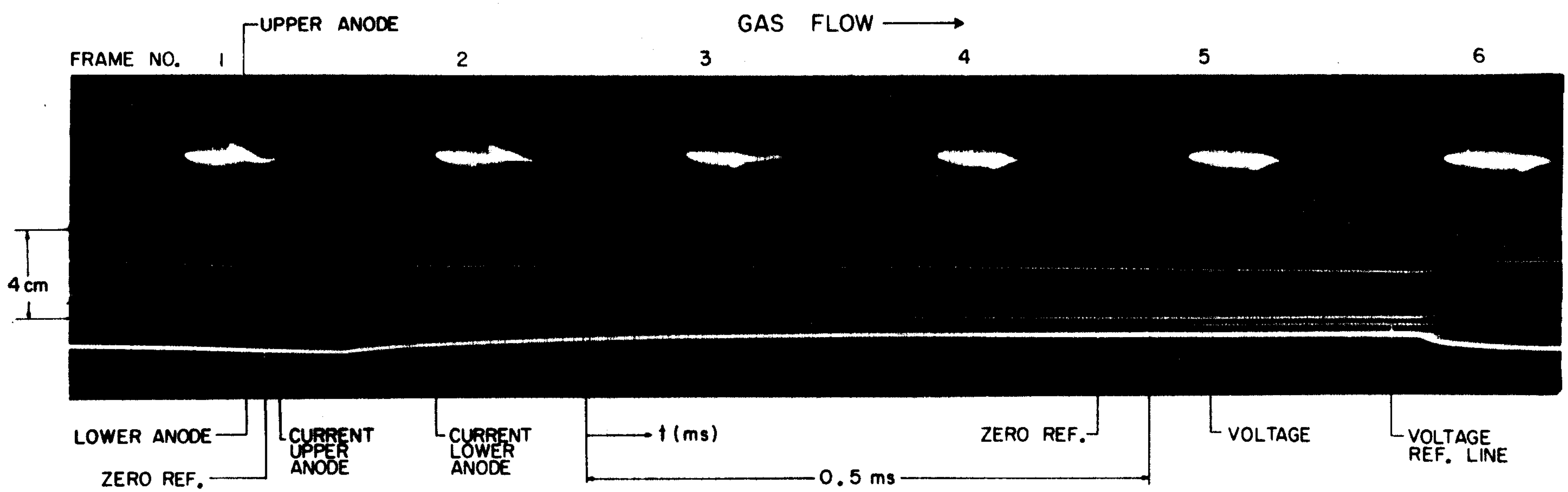


Figure 6. Optical Diagram of Plasmascope (Less Mirrors) and Spectrometer.



V = 30 m/sec , P = 760 mmHg , $\overline{I}$ = 200 Amp , $\overline{U}$ = 34 volt
OSCILLOSCOPE SETTINGS: 200 A/cm , 20 V/cm

FIG. 7: TYPICAL PORTION OF A HIGH SPEED MOVIE FOR ARGON WITH DOUBLE-ANODE

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